Galaxies  Astro 530
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Chemical Evolution in Galaxies  PART 2:
Revenge of the Pre-enriched Leaky Accreting Box
One-Zone / Closed Box Model

• Simplest possible chemical evolution model
• Nothing enters or leaves box
• Initially mass in box is 100% gas, no heavy elements, no stars
• As time goes on, stars form from gas, massive stars explode and return H, He, and heavies to ISM; gas in ISM is gradually consumed and remaining gas becomes increasingly polluted by heavy elements
• Gas is always well-mixed within box

Some stellar systems are roughly consistent with CBM, but many are not, and are instead more consistent with a leaky or accreting box
One-Zone / Closed Box Model

with Instantaneous Recycling (IR) approximation
(best for elements produced by massive stars, e.g. O, Mg, Si)

metallicity of ISM gas
\[ Z(t) = -p \ln \left( \frac{M_g(t)}{M_g(0)} \right) + Z(0) \]

mass in stars as function of metallicity
\[ M_s[<Z(t)] = M_g(0) \left[ 1 - \exp\left\{-(Z(t)-Z(0))/p\right\} \right] \]

mean metallicity of stars after gas gone
\[ \bar{Z}_S = p \sim Z_{\text{sun}} \]

Yield \( p \) = Ratio of:
mass in metals made by stars & returned to ISM to
mass locked up in long-lived stars and compact remnants
(normal yield \( \sim \) solar metallicity \( \sim 0.02 \))
Mean metallicity of bulge stars \( \sim \) solar, as predicted in CBM
AND Fe/H distribution roughly matches CBM with \( p_{\text{eff}} = Z_{\odot} = 0.02 \)

[\textit{although} the bulge has fewer very low mass stars than this model predicts!
and detailed abundances ratios don’t match this model!
So CBM gives decent 1\textsuperscript{st}-order fit to bulge abundances, but not to 2\textsuperscript{nd} order]
bulge star metallicity distribution

Mean metallicity of bulge stars ~ solar, as predicted in CBM AND Fe/H distribution roughly matches CBM with $p_{\text{eff}} = Z_{\text{sun}} = 0.02$

Fulbright+2006
Where does the Closed Box Model work?

Bulge of Milky Way

OK fit (to 1st order) with Closed Box model with IR and reasonable yield $p=2\times10^{-2}$
Where does the Closed Box Model work?

Bulge of Milky Way
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BUT Disk of Milky Way is NOT well fit by CBM (not enough low Z stars -- “G-dwarf problem”)

calculate expected fraction of low-metallicity stars in disk for CBM
Fe/H of nearby (disk) MW F & G stars vs. age

Rough trend of decreasing metallicity with age, but range of metal abundance at any age and galactocentric distance $\rightarrow$ ISM is not well-mixed
Fe/H of nearby (disk) MW F & G stars vs. age

very few disk stars with $Z < 0.25Z_{\text{sun}} \rightarrow \text{“G dwarf problem”}$

closed box model predicts $\sim 50\%$ of stars should have $Z < 0.25Z_{\text{sun}}$
so CBM is wrong for disk!

$[\text{Fe/H}] < -0.4$
Ways that real stellar systems deviate from closed box model

• Pre-enrichment
• Box accretes
• Box is leaky
• Incomplete mixing
Ways that real stellar systems deviate from closed box model

- Pre-enrichment (disk of MW?)
- Box accretes (disk of MW?)
- Box is leaky (globular clusters, low mass galaxies)
- Incomplete mixing (disk of MW)
“G dwarf problem”

contradiction between observations in solar neighborhood and prediction of closed box model is known as “G dwarf problem”

CBM predicts $\sim 50\%$ of stars should have $Z < 0.25 Z_{\text{sun}}$

observations show only $\sim 2\%$ of disk F & G dwarfs have $Z < 0.25 Z_{\text{sun}}$

so CBM is wrong for disk!

one or more of assumptions is wrong...

* box is accreting
* box is pre-enriched

(exact amount of each is still debated...)
“G dwarf problem”

why “G dwarf problem”? this is not the best name. better name: “lack of low metallicity disk stars problem”

want to study sample of long-lived main sequence stars.
O,B,A MS stars – too short-lived
K,M MS stars – too faint to detect lots of them
→ F, G stars – live long enough so there are still old ones around, bright enough to detect large samples
Pre-enrichment ($Z_{\text{initial}} > 0$)

- Initial metallicity of MW disk $> 0$ due to ISM pre-enrichment by star formation in the “spheroid”/bulge which began earlier than formation of (most of?) disk

- Pre-enrichment with $Z_{\text{initial}} \sim 0.1Z_{\odot}$ can solve/partly solve “G dwarf problem” in MW disk (accretion may also be important) amount of pre-enrichment in MW disk still not well known

- Expected to be most important in the disks of massive galaxies with bulges, less (not?) important in globular clusters and low mass galaxies (& bulges themselves)
Accreting Box Model

Ongoing accretion of primordial gas will make metal-poor stars rarer than they would otherwise be

WHY?
Accreting Box Model

Ongoing accretion of **primordial gas** will make metal-poor stars rarer than they would otherwise be.

**WHY?** Instead of forming lots of stars at very early times from very metal poor gas, only a few are formed since the original gas supply is small. If the primordial gas is instead accreted gradually instead of being all available at the beginning, then it mixes with polluted gas, and most stars which form will have a higher Z.
Where does the Closed Box Model work?

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OK fit (to 1st order) with Closed Box model with IR and reasonable yield $p=2\times10^{-2}$

BUT Disk of Milky Way is NOT well fit by CBM (not enough low Z stars -- “G-dwarf problem”)
Solution: Accreting box and/or pre-enrichment

AND MW globular clusters and MW halo and low mass galaxies NOT well fit by CBM (mean metallicity of stars and gas is too low!)
Ways that real stellar systems deviate from closed box model

- Pre-enrichment (disk of MW)
- Box accretes (disk of MW?)
- Box is leaky (globular clusters, low mass galaxies)
- Incomplete mixing (disk of MW)
Leaky Box Model

*Supernovae and O star winds disrupt star-forming molecular clouds, and may also drive gas out of the galaxy*

This will reduce the metallicity of the stars and gas in the system, especially since the massive stars that produce the metals (at least the $\alpha$-elements) drive the outflows
2 spiral galaxies in a small group

M81
Large spiral

M82
Small spiral (starbursting)
Leaking Box: Starbursting spiral galaxy M82

Purple: Hα emission showing outflowing gas driven by supernova winds

M81 & M82 small group
Metallicity distribution of stars in dwarf galaxy VV124

Kirby+ 2012

Low mean metallicity (much less than solar!) requires leaky box with \( p_{\text{eff}}=0.1Z_{\text{sun}}=2\times10^{-3} \)

“pristine model” = leaky box model with no pre-enrichment
“pre-enriched model” = leaky box model with pre-enrichment
“extra gas model” = leaky box plus accretion with no pre-enrichment

Best fit is extra gas model (leaky plus some accretion) (Pristine and pre-enriched model curves overlap in figure)
Fe/H for MW globular clusters

Fe/H distribution of MW globular clusters:
2 distinct populations:
Disk (more metal-rich)
Halo (metal poor)

Fe/H distribution of metal-poor MW halo globular clusters fit reasonably well by leaky box model with $p_{eff}=6\times10^{-4} = 0.03 \ Z_{\odot}$
Fe/H for MW halo stars

Fe/H distribution of MW Halo main sequence stars fit OK by leaky box model with $p_{\text{eff}}=5\times10^{-4}=0.03\,Z_{\odot}$

(fit poor at high Fe/H end – maybe due to disk stars in sample?)

Most halo stars probably come from disrupted globular clusters and low mass galaxies
estimate how leaky galaxies and star clusters might be...
what fraction of gas might be expected to escape?

depends on speed of gas particles $\sigma_{\text{gas}}$ compared to escape speed from system $v_{\text{esc}}$

the speed of particles in a gas depends on its temperature

$$\sigma_{\text{gas}} = \left(\frac{kT}{\mu m_p}\right)^{1/2} = 116 \left(\frac{T}{10^6 \text{ K}}\right)^{1/2} \text{ km/s}$$

since star formation always produces hot gas (and gas at $T \sim 10^6$ K can’t easily cool), a significant quantity of gas associated with star formation will have

$$\sigma_{\text{gas}} = (1-\text{few}) \times 100 \text{ km/s}$$

this is overly simple – might also have cool gas accelerated to high speeds by momentum transfer
*how does this compare to escape speed?*

escape speed depends on the depth of the gravitational potential well, which is related to stellar velocity dispersion (for E’s) or rotation speed (for S’s)

\[ v_{\text{esc}}^2 = 2 |\phi| = 2 f \sigma_*^2 \]

\( \phi \) = gravitational potential per unit mass

\( f \) = number \( \sim 1 - a \) few

\( \sigma_* \sim 5\text{-}10 \text{ km/s for globular cluster, dwarf spheroidal galaxy} \)

\( \sigma_* \sim 200 \text{ km/s for large elliptical} \)

*SO expect most of hot gas to escape from star clusters and dwarf galaxies, much less to escape from large galaxies*
How leaky is box?
escape velocity vs. effective yield

<table>
<thead>
<tr>
<th>system</th>
<th>$v_{esc}$</th>
<th>$p_{eff}$</th>
<th>$p_{eff}$</th>
<th>model</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW bulge</td>
<td>~500 km/s</td>
<td>2.0x10^{-2}</td>
<td>1.0 $Z_{sun}$</td>
<td>Closed box</td>
</tr>
<tr>
<td>dIrrs + dEs</td>
<td>~100 km/s</td>
<td>2.5x10^{-3}</td>
<td>0.13 $Z_{sun}$</td>
<td>Leaky box</td>
</tr>
<tr>
<td>Metal poor globulars</td>
<td>~10 km/s</td>
<td>6.0x10^{-4}</td>
<td>0.03 $Z_{sun}$</td>
<td>Very leaky box</td>
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(mean metallicity of stars and gas is too low!)
Solution: Leaky box
metallicity-stellar mass relation for 53,000 nearby galaxies (z~0.1):
sample of SDSS spectra & fibers

gas-phase O/H estimated by fitting many spectral emission lines with photoionization code

SDSS fiber covers 3” about galaxy center. for some galaxies this is ~all of galaxy; for others it is only central region; despite this, SDSS central fiber often used to characterize entire galaxy (may not always be appropriate)

Tremonti+2004
relation between observed spectral lines and *gas-phase metallicity*

\[ \frac{[\text{OII}]+[\text{OIII}]}{H\beta} \]

is pretty good tracer of gas-phase O/H: using both [OII] and [OIII] lines captures gas with both high and low excitation

**Tremonti+2004**

O/H estimated by fitting many spectral lines with photoionization code

solar metallicity = 8.7
optical spectrum of HII region

\[ R23 = \frac{[\text{OII}]+[\text{OIII}]}{\text{H}\beta} \]

use sum of [OII] and [OIII] lines to capture different ionization states of Oxygen
which single element can characterize overall “metallicity”?

• no single element can – there are important variations among elements

• for gas, “metallicity” often taken as O abundance (strong emission lines, not strongly depleted onto dust grains)

• for stars, “metallicity” often taken as Fe abundance (many strong absorption line)
metallicity-stellar mass relation for 53,000 nearby galaxies ($z \sim 0.1$) from SDSS spectra

galaxy mass determines gas-phase metallicity to within factor of $\sim 2$
(not much scatter $\sim 0.1$ dex)

metallicity drops 5x as stellar mass drops 100x (from $10^{10.5}$ to $10^{8.5}$ $M_\odot$)

$\rightarrow$ gas escapes more easily (leakier box) in low mass galaxies

Tremonti+2004
Virgo cluster galaxies have fewer metals → even leakier boxes due to ram pressure stripping

lost 50%, 90% of metals

true yield (if no metals lost)

Virgo cluster galaxies have fewer metals → even leakier boxes due to ram pressure stripping

Tremonzi+2004

effective yield – baryonic mass relation

low-mass dwarf galaxies are 5 times more metal depleted than \( L^* \) galaxies at \( z \sim 0.1 \).

metal depletion also found in galaxies with masses as high as \( 10^{10} M_\odot \).

→ galactic winds can remove metals from even large galaxy potential wells.
• not all places in a given galaxy have same metallicity

• not all “heavy elements” are the same: relative abundances of different heavy elements vary in ways that give insight into galaxy formation & evolution
Metallicity lower in outer disks – corresponds to higher gas mass fraction ($\Sigma_{\text{gas}}/\Sigma_{\text{star}}$) associated with longer gas depletion timescale ($\Sigma_{\text{gas}}/\Sigma_{\text{SFR}}$) in outer disk so yield could be the same (but maybe also due to accretion happening more in outer disk, or outer disk leakier?)

Unbarred spiral galaxies generally have metallicity gradient, but Barred Galaxies generally do not → suggests radial mixing due to bar-driven gas flows
Where metals in ISM come from

- **H, He, Li, Be, B** – Big Bang
- **C, N** – much of this comes from stars with $M \sim 1$-few $M_{\text{sun}}$, which eject envelopes as PN, (happens ‘slow’ $> 1$ Gyr, so IR appx not great)(some also comes from Type Ia & II SN)
- **“$\alpha$-elements”**: (O, Ne, Mg, Si, S, Ar, Ca and Ti) made by adding He ($\alpha$ particle) to C, O, etc; happens mostly in $M > 10M_{\text{sun}}$ stars which return elements to ISM thru Type II SN (happens ‘fast’, $>100$ Myr, so IR appx OK)(Fe and other heavier elements get locked into NS or BH core)(these are “primary” elements, whose production does not depend on the presence of other heavy elements)
- **“iron peak”** (V, Cr, Mn, Fe, Co & Ni) made mostly in white dwarf stars which explode as Type Ia SN, no core left (happens ‘slow’ $> 1$ Gyr, so IR appx not great)
- **heavier than iron** – SNe explosions, merging neutron stars
nucleosynthesis periodic table
**O/Fe ratio vs. Fe/H ratio in MW stars**

- **some stars enriched in ‘fast return’ elements (α elements e.g., O) relative to ‘slow return’ elements (e.g., Fe)**
- stars of low metallicity are relatively richer in α elements than iron peak elements
  → in halo star formation occurred early and ended before much Fe (from older stars) got returned to ISM

[Graph showing O/Fe vs. Fe/H ratios for different stellar populations: MW disk, MW thick disk, MW halo.

* MW disk
* MW thick disk
* MW halo

SG4.17 (Bensby)